NATIONAL

SPACE TRANSPORTATION STRATEGY

# NATIONAL SPACE TRANSPORTATION AND SUPPORT STUDY

## 1995-2010

Prepared by Joint Steering Group

MAY 1986

NATIONAL SPACE TRANSPORTATION AND SUPPORT STUDY

SUMMARY REPORT

14 May 1986

Prepared by Joint Steering Group

Approved:

| DOD | NASA |
|---|---|
| Edward C. Aldridge, Jr., Cochairman<br>Under Secretary of the Air Force<br>May 14, 1985 - April 11, 1986 | Jesse W. Moore, Cochairman<br>Associate Administrator<br>of Space Flight, NASA<br>May 14, 1985 - February 19, 1986 |
| Bernard P. Randolph, Cochairman<br>Lieutenant General, USAF<br>Deputy Chief of Staff,<br>Research, Development and Acquisition<br>April 12, 1986 - Present | Richard H. Truly, Cochairman<br>Rear Admiral, USN<br>Associate Administrator<br>of Space Flight, NASA<br>February 20, 1986 - Present |

## JOINT STEERING GROUP MEMBERSHIP

NASA

- o Jesse W. Moore, Associate Administrator of Space Flight (through February 19, 1986)
- o R. Adm. Richard H. Truly, Associate Administrator of Space Flight (effective February 20, 1986)
- o Dr. William R. Lucas, Director, George C. Marshall Space Flight Center
- o Norman E. Terrell, Associate Administrator for Policy
- o Dr. Raymond S. Colladay, Associate Administrator for Aeronautics and Space Technology

DOD

- o Edward C. Aldridge, Jr., Under Secretary of the Air Force (through April 11, 1986)
- o Lt. Gen. Bernard P. Randolph, USAF Deputy Chief of Staff, Research, Development, and Acquisition
- o Lt. Gen. James A. Abrahamson, Director, Strategic Defense Initiative Organization
- o Dr. Larry L. Woodruff, Office of the Under Secretary for Defense Research and Engineering (Strategic and Theatre Nuclear Forces)

Two Executive Secretaries were appointed to the Joint Steering Group as non-voting members. Ivan Bekey, Director of Advanced Programs, Office of Space Flight, represents NASA, and Dr. Thomas P. Rona, Office of Secretary of Defense, represents DoD.

Codirectors of the Joint Task Team are Paul F. Holloway, Deputy Director, NASA Langley Research Center, and Col. William F. H. Zersen, Assistant for Advanced Launch Systems, Deputy Commander for Launch and Control Systems, USAF's Space Division. Darrell Branscome, NASA Office of Space Flight serves as Mr. Holloway's Deputy.

# FOREWORD

This report summarizes the findings and recommendations of a year-long cooperative study by the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA). Detailed data, discussions, and study rationale are presented in the expanded Overview document and its supporting annexes.

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## I. BACKGROUND AND PURPOSE

National Security Decision Directive (NSDD) "National Security Launch Strategy," was signed by President Reagan on 25 February 1985. This decision directive presents guidance for near-term implementation of the policies delineated in a prior National Security Decision Directive "National Space Strategy." The latter NSDD stated that the Space Transportation System (STS) will continue as the primary space launch system for both national security and civil government missions and directed that DoD pursue an improved, assured launch capability that will be complementary to the STS to ensure the national security launch requirements are met. The February 1985 NSDD also specified that:

> "DoD and NASA will jointly study the development of a second-generation space transportation system -- making use of manned and unmanned systems to meet the requirements of all users. A full range of options will be studied, including Shuttle-derived technologies and others."

To implement the 25 February decision directive, the President signed a National Security Study Directive (NSSD) in May 1985. This document directed that a joint DoD/NASA study be accomplished within one year and delineated four tasks which would provide the basis for a space transportation technology program plan:

- Task 1. Compile sets of national security and civil space mission classes for the 1995 period and beyond.
- Task 2. Determine space transportation system capabilities which could cost-effectively support the mission needs specified in Task 1.
- Task 3. Identify the transportation technologies that are necessary and could be available for the systems to be used in the post-1995 period.
- Task 4. Based on the technological needs and opportunities specified in Tasks 2 and 3, identify the technology development programs needed for timely realization.

Four objectives or guiding principles were specified for the joint study:

- o Satisfy the future needs of authorized users
- o Substantially reduce the cost of space operations to the government
- o Develop a flexible and robust space transportation system
- o Maintain world leadership in space transportation

In preparing for the study, the existing U.S. space transportation capabilities and related activities were evaluated. The key lessons learned are as follows:

- o The current launch systems of the U.S. represent the best technology and the best operations costs available at their individual initial operating dates. Viewed as an architecture, they have kept the U.S. in the dominant leadership role in space transportation. However, in planning for the 1995-2010 time period, achieved plus readily achievable technology advances must be exploited to ensure that the current U.S. leadership posture is maintained.
- o The current systems were originally designed to meet space mission planning models which never fully materialized.
- o Funding limitations during the development phases of current systems precluded existing national launch systems from realizing full potential for cost-effective operations.
- o A complementary strategy (i.e., no dependence on a single launch system) must be inherent in the national space policy to increase the probability of continuous access to space.
- o Space transportation costs have been substantially driven by both launch system and spacecraft designs which require lengthy manpower-intensive, technically complex, high-cost integration efforts. Too frequently, special spacecraft and launch system modifications and high-performance (low margin, experimental-type operations) missions are required to meet spacecraft- unique needs.
- o The nation has neither funded nor maintained a vigorous advanced space transportation technology program to improve the operational effectiveness of the existing national launch systems nor provided the appropriate technical foundation for future launch systems.

- The national launch systems industrial base cannot rapidly react to changing space launch requirements and/or adversity.
- Substantial reductions in space transportation costs must be attained if the nation is to meet the demanding needs of the future.
- Foreign space-related developments are beginning to erode the United States' preeminence in space launch activities. The U.S. technology and system development efforts must be made in the context of vigorous and increasing international competition.

## 2. MISSION NEEDS

Technology initiatives must be defined in terms of potential system concepts within the future robust space transportation architecture for satisfying space mission needs. Therefore, sets of space mission classes have been compiled independently by DoD and NASA which reflect potential national security and civil (government and commercial) space traffic, respectively, for the time period 1995 through 2010. These space mission sets are representative only for the purpose of identifying system capability and related technology needs, and they do not constitute specific plans or requirements for either DoD or NASA. Particular attention was given by DoD to the emerging requirements of the President's Strategic Defense Initiative (SDI), and NASA consulted with the National Commission on Space during the development of these space mission sets.

Because it is not possible to precisely predict the level or nature of future space activities, DoD and NASA each developed four alternative sets of projected mission needs reflecting different space traffic levels. Five combinations of these sets were selected to ensure that mission needs from constrained through aggressive cases were modeled. These five mission model cases are detailed in Table 1.

The Constrained Case, the lowest projected level of national space activity, comprises contemporary national security missions, a low level of SDI experimentation, and a civil core program. The latter includes a permanently manned Space Station, as well as both domestic and foreign components encompassing science and applications, technology developments, and commercial activities. The Normal Growth Case adds some new DoD program starts, has increased levels of SDI experimentation, and includes

## Table 1. National Space Mission Case Construction

| Case | Civil Option | | DoD Scenario |
|---|---|---|---|
| CONSTRAINED | Core Program<br>- Ongoing Civil Discipline Programs<br>o Science and Applications<br>o Technology Development<br>- LEO Space Station<br>- Polar Platform<br>- GEO Experiments Platform<br>- LEO Space Station Growth | (1992-2010)<br><br><br>(1994)<br>(1994)<br>(1998)<br>(1997, 2003) | Constrained Activity<br>- Contemporary Missions/Spacecraft<br>- Low Level of SDI Experiments |
| NORMAL GROWTH | Baseline Program<br>Civil Option I Plus:<br>- GEO Sorties and Shack<br>- GEO Manned and Automated Servicing<br>- Lunar Sortie | (2002, 2006)<br>(2004)<br>(2009) | Normal Growth<br>- Adds Advanced Missions and New Starts (AF, Navy, DNA)<br>- Increased Level of SDI Experiments<br>- Adds Advanced Payload/ Operations/Servicing Capabilities Development |
| MODEST EXPANSION PARTIAL SDI | Modest Expansion<br>Civil Option II Plus:<br>- Second LEO Space Station<br>- Mars and Asteroid Sample Returns<br>- Commercial Growth<br>- Quarantine Facility | (2008)<br>(2004, 2008)<br>(1996)<br>(2003) | SDI KEW<br>- Adds Operational KEW, SSTS Deployment<br>- Adds KEW, SSTS Servicing Missions<br>- Reduced Level of SDI Experiments |
| FULL SDI | Baseline Program<br>Same as Civil Option II Above | | Full SDI<br>- Adds Operational DEW Deployment, Servicing<br>- Transition to Advanced SSTS |
| AGGRESSIVE CIVIL | Aggressive Expansion<br>Civil Option III Plus:<br>- Earlier Deployment Dates for Most Programs<br>- Lunar Surface Camp and Orbit Station<br>- Manned Mars Mission Buildup<br>- Nuclear Waste Disposal (Solar Orbits)<br>- Third LEO Space Station<br>- Space-Based Energy<br>- Public Access<br>- Extended Communications | (2006, 2008)<br>(2012)<br>(1998)<br>(2007)<br>(2007)<br>(2008)<br>(2001) | Normal Growth<br>Same as DoD Scenario 2 above |

manned civil missions in geosynchronous orbit and lunar sorties. The Modest Expansion/Partial-SDI Case is principally characterized by the addition of a representative SDI kinetic energy weapon (KEW) deployment, a second Space Station, and Mars/Asteroid sample returns. The Full SDI Case postulates increased emphasis on national security space activities, including very extensive SDI operational deployments of directed energy weapons (DEWs), and the Aggressive Civil Case postulates substantially expanded civil space activities encompassing a broad spectrum of space exploration and earth-focused programs.

Significant transportation requirements derived from the mission models are:

- o For any of the five cases, traffic to orbit would be higher than present day levels, both in terms of weight to orbit and frequency of flight. Spacecraft, payloads, flight crews, and servicing materials to be orbited range from approximately 1.25 to 1.75 million pounds annually for the lower activity level cases (Constrained and Normal Growth) to upwards of 5 million pounds annually for the Full-SDI and Aggressive Civil Cases. The orbit transfer system (OTS) weights necessary for transporting selected items beyond low earth orbit (LEO) represent a sizable additional transportation need.
- o The national security and civil space missions both involve continued spacecraft and payload placements into the variety of orbits being used by present day U.S. space traffic. However, a new class of orbits (mid inclination, low altitude) not used today would experience the largest traffic levels if operational SDI spacecraft were deployed. Depending on the types of space transportation systems ultimately developed, significant activity increases at the Western Test Range (WTR) or a new launch site could be required to accommodate this SDI traffic.
- o Potential SDI architectures involve large satellite constellations to provide continuous coverage of the earth. Establishing such constellations would introduce new requirements for precise timing of launches and orbit transfers to achieve proper orbital plane placements and mission control of multiple spacecraft orbit transfers occurring simultaneously.

- Manned operations in space are a significant element of the civil space program for the first Space Station beginning in the mid-1990s and for geosynchronous earth orbit (GEO) servicing and lunar sorties beyond the turn of the century. In the most aggressive civil option, manned missions to the Moon and to Mars are projected. Potential roles for man in national security space missions are still under study. Assured return from space will be an important transportation requirement.
- Space servicing activities include maintenance, replacement, upgrade, assembly, checkout, retrieval, return, and repair. Approximately half of the civil mass transportation needs are devoted to space servicing, and DoD spacecraft servicing requirements could evolve.
- Some national security space operations must be possible during various conflict levels or natural adversity (e.g., to supplement, redeploy, or replenish space assets), and selected space transportation systems will therefore have to satisfy more stringent functional/operational needs in such areas as availability (readiness to operate when required, regardless of the circumstances), performance margins, flexible response to changing situations, survivability, and positive control. Specifics of these functional/operational needs are being developed by the new Unified Space Command in consonance with the evolution of its strategies and by the SDI Organization.

## 3. ARCHITECTURES

Space transportation architecture issues for the post-1995 time period derive from the nature of the existing (pre-1995) space transportation architecture as well as from the combined DoD/civil mission model sets. Unless there are new initiatives, the U.S. would enter the post-1995 time period with a relatively high-operating-cost space transportation architecture consisting principally of a modest Shuttle fleet with ground processing and launch facilities at both the Eastern Test Range (ETR) and WTR designed for limited launch rates. The architecture existing then could also include the Complementary Expendable Launch Vehicle (CELV) presently planned for launch from ETR to provide an increased assured access probability for critical DoD spacecraft and possibly other expendable launch vehicles (e.g., Delta, Atlas, and Titan II). The use of two CELVs per year is anticipated upon its introduction in 1988, though planned utilization

rates and launch sites are presently undergoing review. The pre-1995 space transportation architecture will have a number of OTSs including Centaur G, Centaur G', the Payload Assist Module (PAM) Series, the Inertial Upper Stage (IUS), and the Transfer Orbit Stage (TOS). Orbital Maneuvering Vehicles (OMVs) with a robotic smart front end would be utilized extensively in any future architecture for payload positioning and for assembly and servicing operations. The OMV is under development and will be operational prior to 1995, but the smart front end introduces additional technology requirements.

The existing space transportation architecture would be unable to effectively handle the increased traffic anticipated for the post-1995 time period. Just to accommodate the Normal Growth Case flight rates, expenditures for additional Orbiters, expendables, facilities, and operations personnel at both ETR and WTR would be needed. Further substantial expenditures at WTR would be required for an SDI-KEW deployment. Such expenditures could perpetuate the use of a relatively high-operating-cost transportation architecture and preclude the opportunity to exploit technology advances and innovative operations approaches which can significantly reduce costs.

Space traffic growth beyond the mid-1990s leads to a preferred architecture employing two new launch systems (an unmanned cargo vehicle and a new manned vehicle); a new, reusable OTS; and new, innovative launch and flight operations approaches (supplementary use of contemporary expendables for selected, specific missions cannot yet be ruled out). This preferred architectural approach has been shown to be cost effective over a broad range of mission scenarios. The unmanned cargo vehicle could effectively replace the CELVs, complement the Shuttle cargo capability, and help to increase probability of assured access to space.

Even with an unmanned cargo vehicle (UCV) introduced in the mid- to late-1990s, a new manned vehicle is necessary after the turn of the century for a more cost-effective, robust space transportation architecture. The then existing Shuttle fleet will be reaching lifetime limits and would represent 25-year-old technology. Therefore, architectures involving two new vehicles, a UCV followed by a new manned vehicle (and supplemental use of contemporary ELVs), have become the prime focus of ongoing space transportation activities. For two stage options, common elements, such as the booster first stage for both the UCV and new manned vehicle, appear effective in terms of life-cycle costs, but

this approach must be assessed for soundness of assured access. (The Full SDI Case would require substantial development expenditures for an additional, heavy-lift, unmanned cargo vehicle to launch the large DEWs if their modularization proves impractical.)

There are numerous launch vehicle system options, as well as OTS options, for structuring such architectures (see Figure 1), all of which are currently under study. Additionally, new systems and approaches for launch and flight operations which would significantly lower costs are being identified and assessed. Alternative architectures comprised of various combinations of these system options are being evaluated using cost, performance, operations, operational availability and flexibility, risk, safety, world transportation leadership, and other political/programmatic considerations.

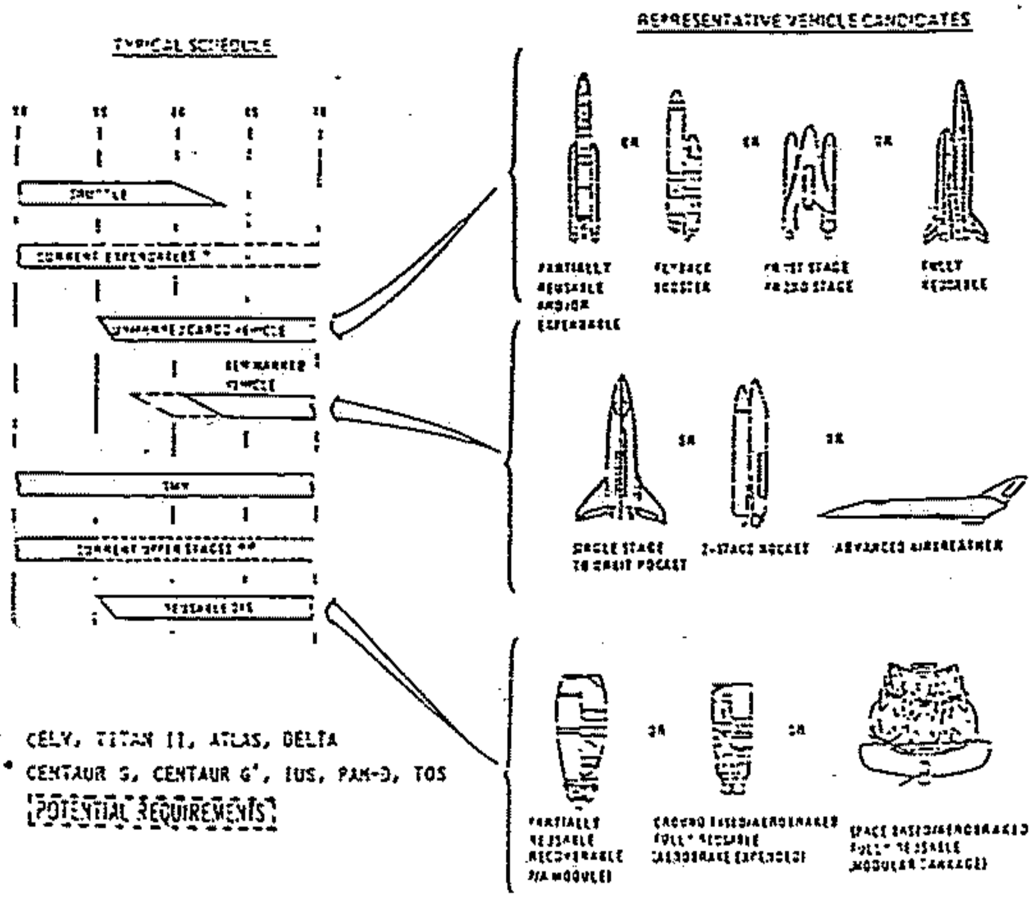



Figure 1. Representative Architectures

The concepts evaluated ranged from single- and two-stage rocket systems to the emerging airbreathing engine technologies. The application of advanced materials, structures, and engines could dramatically increase the performance and decrease the weight and size of rocket vehicles. Simple, highly automated, and airline-like procedures could lead to very low-cost manned or unmanned rocket vehicle operations. A new concept to achieve orbit is the airbreathing National Aero-Space Plane (NASP) Program. The NASP is a focused technology program with an FY 1988-1989 decision date leading toward an FY 1993 technology demonstration research aircraft with a horizontal takeoff and landing single-stage-to-orbit potential. This approach could have a major impact on any future space architecture. Possible operational implications include operation from military airfields, high flight rate, survivability, and flexibility. A NASP vehicle with these characteristics could alter the nature of the entire logistics, operations, and support systems.

## 4. TECHNOLOGY ASSESSMENTS

Ongoing architecture studies have not progressed far enough to permit firm choices of specific system elements. Hence, only broad conclusions about life-cycle cost reductions can presently be drawn. However, a preferred generic architecture has been identified and used together with knowledge of the high cost aspects of current transportation systems to identify areas of high cost reduction potential. Figure 2 illustrates a sample generic launch vehicle architecture and supporting technologies. Technology projects required to achieve these cost reduction potentials were determined and structured into an overall integrated technology program. Establishment of priorities for the various technology projects in order of benefits versus costs is one of the next steps for the architecture study to accomplish. While these cost/benefit evaluations have not yet reached the point of rigorous quantification, there are clear indications that the cost savings will be large. For the architecture described above, the studies currently indicate very large leverage factors (ratios of life-cycle cost reduction to technology investment). Technology investments of 1-3 percent of the total life-cycle costs (for architectures like that shown in Figure 2) are found to produce significant life-cycle cost reductions with operations costs approaching an order-of-magnitude reduction from present day levels. Without such reductions in operations costs, it is questionable that we could afford even the lowest level of mission model activity, as identified in this study.

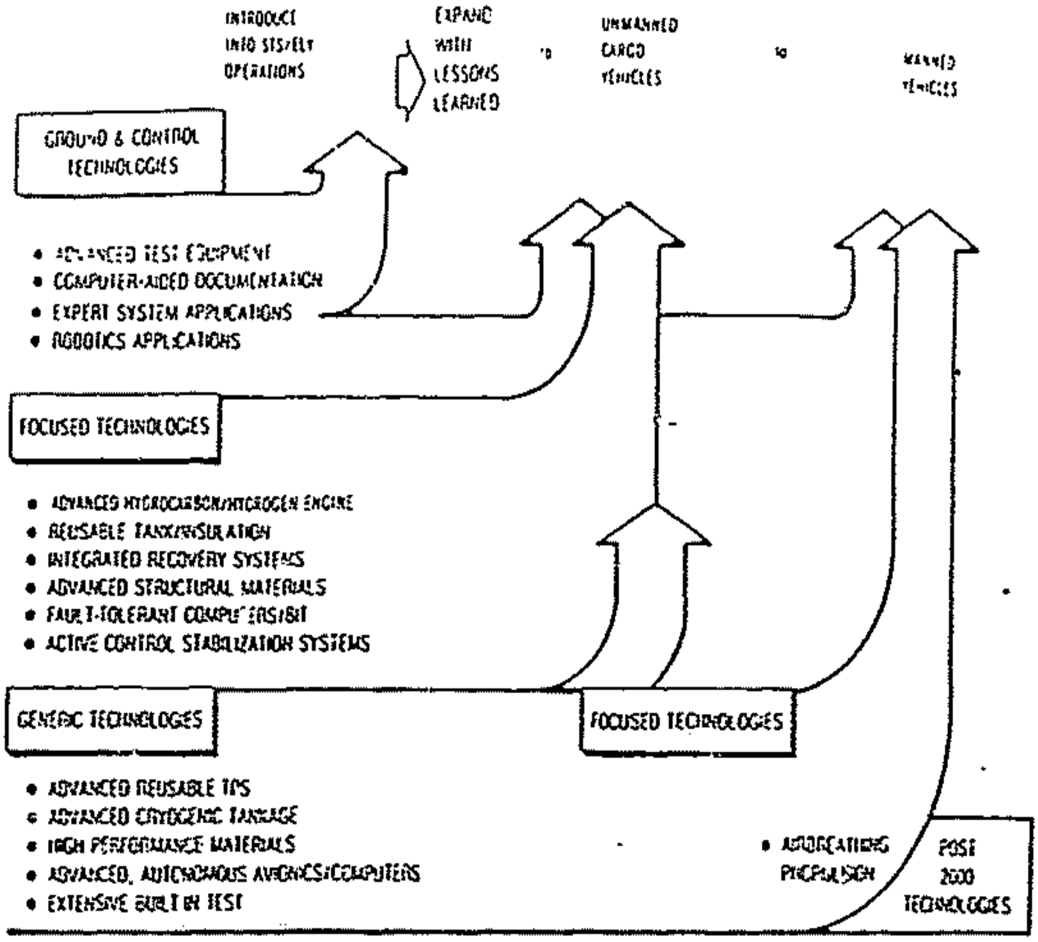



Figure 2. Typical Launch Vehicle Architecture with Supporting Technologies

Cost benefits can be derived through the application of advanced technology in each of the segments of a transportation architecture. These segments are launch operations, flight operations, launch vehicles, and OTS stages. The effect of technology on cost reduction in each of these segments will be addressed. Certain of these technologies are synergistic, but their impact will be discussed topically. Examples of key technologies identified as having high-leverage payoff are illustrated in Table 2.

o Launch Operations

To achieve cost benefits in launch operations, functional flows must be structured to minimize vehicle and pad turnaround time. This may require that all vehicle assembly,

Table 2. Key High-Leverage Technologies Applicable to Architectures

| Technology Area/Items | Rationale | Mid- to Late-1990s* IOC Systems | Post-2000 IOC Systems |
|---|---|---|---|
| Avionics/Software/Automation | | | |
| AI/Expert Systems | Minimize Ground Support | o | o |
| Fault Detection/Isolation | Minimize Ground Support | o | o |
| Adaptive G&C | Minimize Ground Support | o | o |
| Software Automation | Minimize Ground Support | o | o |
| Structures/Materials | | | |
| Hot Structures (>1000°F) | Increase Reuse | | o |
| Active Cooling | Extend Operating Regime | | o |
| Reusable TPS | Minimize Refurbishment | o | o |
| New Alloys and Composites | Increase Performance | o | o |
| Advanced Carbon/Carbon | Extend Reuse | o | o |
| Ground/Flight Operations | | | |
| Computer-Integrated Manufacturing | Reduce Manufacturing Cost | o | o |
| Automated Launch Processing and Mission Control | Minimize Ground Operations | o | o |
| AI/Expert Systems for Planning, etc. | Minimize Ground Operations | o | o |
| Robotic Systems for Handling, Servicing, etc. | Minimize Ground Operations | o | o |
| Automated Space Operations and Logistics (Servicing) | Minimize Ground Operations | o | o |
| Software Automation | Minimize Ground Operations | o | o |
| Propulsion/Power | | | |
| LOX/HC Engine | Optimize Vehicle | o | o |
| $LOX/LH_2$ Engine | Increase Life, Performance | o | o |
| Cryo OTS Engine | Improve Performance | o | o |
| Clean, Low-Cost Solid | Lower Cost, Reduce Pollution | o | o |
| Advanced Engine (Airbreathing) | Extend Performance | | o |
| Cryo Propellant Storage and Transfer | Permit Orbital Operations | o | o |
| Aerothermodynamics/Flight Mechanics | | | |
| Aerobraking | Improve Performance | o | o |
| Advanced Recovery | Minimize Cost | o | o |

*IOC date references mission requirement need, not technology availability date (TAD). TAD must be compatible with IOC.

checkout, and integration of payloads be accomplished off pad and that flight vehicles be transported to the pads ready for fueling and launch operations. The technology advances required to support these operations, some of which are vehicle related, are:

- o Expert systems and artificial intelligence for use in subsystem fault detection and isolation, vehicle checkout, and launch.
- o Precision recovery systems that will permit recovery operations in close proximity to refurbishment areas, thus reducing logistics costs and turnaround times.
- o Advanced thermostructures including advanced tankage concepts, thermal protection systems (TPSs), and lightweight high-temperature structures that will need minimal refurbishment between flights.
- o Simplification and standardization of payload interfaces with the launch vehicle approaching the containerization-type procedures used in most other mature transport systems.
- o Avionics system improvements such as on-board fault detection, isolation, and diagnosis.
- o Vehicle propulsion systems designed to operate at less than maximum performance capability, thus requiring less maintenance and refurbishment.

o Flight Operations

Preflight planning and operations, two of the major flight operations cost drivers in present day systems, are highly interrelated. Since both are labor and documentation intensive, reductions over present day operations are achievable by reducing documentation and the associated labor costs, improving configuration management, and integrating pre-mission operations. Study results also showed that a substantial reduction from Shuttle flight operations costs will be possible when new vehicles incorporating advanced technology are available and vehicle autonomy is employed. The technologies required to support these concepts include:

- o Automated software generation, validation, and integration, which will reduce software life-cycle costs, especially in operations and maintenance, and provide more rapid and reliable software generation and computing for high-speed flight control; avionics system improvements which allow significant autonomous operation.
- o Adaptive guidance, navigation, and control which will achieve on-demand launch/recovery, precision rendezvous, and docking and in-space operations without ground support.
- o Flight systems management in the areas of automated system health determination, on-board mission planning and targeting, and flight operations management.
- o Artificial intelligence that will increase the rapidity and accuracy of fault diagnosis and reduce on-line manpower needs.
- o Telerobotics which can increase space productivity and enable automated servicing and repair operations.
- o An advanced information processing system utilizing the paperless management concept.

o Launch Vehicles

Trends and observations which can guide selections of needed technologies have resulted from the architecture and system studies. These include the degree of reusability, automated production techniques, and down-payload capability. Systems incorporating a higher degree of reusability appear to offer life-cycle and operations cost advantages that increase as traffic levels increase. Appropriate technologies for reusability must be developed and verified as a part of the technology program. Also, improved, more automated production techniques could enhance the attractiveness of the assured access capabilities of expendable launch and orbit transfer systems. Consequently, technology programs should be concerned with production-related as well as performance-related requirements. Finally, technology should be concerned with a down-payload capability as incorporation of this idea into an unmanned cargo vehicle could be a desirable feature.

Launch vehicle characteristics drive the total transportation system costs because of their acquisition and operational hardware costs and through their impact on the launch and flight operations costs. Development and production costs can be reduced by incorporating current and future improvements in computer-aided design and manufacturing, in analytic tools, and in engineering and management automation. Development of advanced analytical tools and computer programs in the areas of fluid mechanics, structural loads and dynamics, and thermal analysis will provide major reductions in costly system-level testing. The combined effect of these improvements should significantly reduce development costs.

For a given payload delivery capability, improvements in performance- related technologies result in smaller and lighter launch vehicles and reduced operations costs. Areas of such technology applications include new, efficient advanced rocket (LOX/HC and LOX/$HO_2$) propulsion systems; lightweight materials; hot structures; robust, reusable TPSs; and airbreathing advanced propulsion systems.

Reducing vehicle maintenance and refurbishment requirements through changes in vehicle design can have a major impact on ground operations costs. Some of these changes are directly coupled to designs incorporating higher vehicle performance margins. If high margins are used to reduce operating levels of components such as main engines and fluid/mechanical systems, dramatic maintenance cost reductions and increased life can be achieved. Additional reductions are possible through improvements in TPSs or through the use of lightweight, high temperature materials in structures which will not require a TPS. Reduction in the number of vehicle elements and simplification of interfaces will reduce ground operations and integration costs. Increasing the vehicle's ability for self test will reduce test and checkout costs, but it will increase avionics and software size and complexity.

- Orbit Transfer Systems

Key factors in reducing the operational cost associated with high-energy missions are reusability as well as propellant selection. The $LO_2/LH_2$ and storable-propellant engines are the most likely candidates for OTSs in the near term. Modularity is necessary to provide flexibility to accommodate a variety of payload sizes and weights efficiently.

Technology for cryogenic fluid storage and management in a zero-g environment will be required for a spaced-based OTS which effectively uses a space platform as a transportation mode. Reusable vehicles will require a new engine with adequate life and with diagnostic instrumentation.

An aeroassist OTS has been studied and has the potential for cost savings since it reduces the weight and cost of propellants for orbital transfer. New technology required for a deployable, heat-resistant aeroshield is currently being considered.

## 5. TECHNOLOGY PLAN

Future space transportation system alternatives are totally dependent upon near-term decisions affecting the direction and magnitude of investment in essential enabling and enhancing technologies. The study directive, underscoring the need to revitalize the nation's launch and logistic support technology base, specifically tasks this study to identify those technologies that might be made available for use in the post-1995 period and to define the associated investment strategies and technology development programs required to support the architectures under consideration. Study results presented in this report have provided a basis for a comprehensive national technology plan that:

- Strongly emphasizes those innovative technologies that will significantly reduce the costs of launch and flight operations.
- Supports improvement for existing vehicles and future development of a low-cost unmanned cargo vehicle.
- Vigorously pursues the long-term progressive evolution of the necessary technologies that will ensure high-performance, fully reusable, low-operations-cost, manned vehicles in the post-2000 timeframe.
- Utilizes demonstration programs to focus individual technology projects, initiate multidisciplinary research, and verify the low- risk availability of new technology developments for application to operational systems.

o Technology Projects and Demonstration Programs

High-leverage technology areas pertaining to operations/logistics and vehicle performance/reusability have been identified in the technology assessment and emphasized in the technology plan development. These include:

OPERATIONS/LOGISTICS

- Autonomous expert systems with artificial intelligence for use in subsystem fault detection and isolation, vehicle checkout and launch, and mission planning and control
- Automated software generation, validation, and integration
- Advanced avionic subsystems and fault-tolerant electronics
- Computer-integrated design, manufacturing, and logistics
- Telerobotics and on-orbit servicing
- Advanced information processing systems

PERFORMANCE/REUSABILITY

- Advanced rocket and airbreathing propulsion systems
- Lightweight, high temperature materials and structures
- Durable, reusable thermal protection systems
- Adaptive guidance and control, autonomous navigation
- Aeroassist for orbital transfer systems
- Zero-g cryogenic fluid storage and management
- Precision recovery systems for partially reusable launch vehicles
- Computational fluid dynamics and structural analyses

These technology areas have been structured into individual technology program elements related to the generic vehicles being considered for future architectures (see Table 3). Each program element has been further detailed in terms of its objectives, approach, funding profiles, major milestones, and system-level payoffs (see typical example, Table 4). The recommended program establishes a firm technology base that will allow the nation to confidently select and proceed with any of the alternatives which might result from the architecture studies.

The transition of technology elements from completed research and technology development projects to operational flight or ground service must overcome the formidable difficulties of system integration. This is best accomplished by technology demonstration programs which are system-level initiatives, typically flight experiments or ground tests, designed to be compatible with expected environments and operational

Table 3. Technology Program Elements vs. Generic Vehicles

TECHNOLOGY PROGRAM ELEMENTS — AEROTHERMODYNAMICS/FLIGHT MECHANICS

| Vehicle | Ground test facilities | Computational fluid and aerothermodynamics | Aerothermodynamic data base models | Ascent aerodynamics | Upper atmosphere aerodynamics | Low speed fluid dynamics |
|---|---|---|---|---|---|---|
| SHUTTLE OPS WITH IMPROVEMENTS | | | ● | ● | ● | |
| ADVANCED CARGO VEHICLE | ● | ● | ● | ● | ● | |
| IMPROVED EXPENDABLE ELV | | | | | | |
| OMV | | | | | | ● |
| REUSABLE OTV | ● | ● | ● | | ● | ● |
| HEAVY LIFT CARGO VEHICLE | | ● | ● | ● | ● | |
| MANNED REUSABLE VEHICLE | ● | ● | ● | ● | ● | |
| HIGHLY AUTONOMOUS OMV | | | | | | ● |
| SPACE BASED OTV | ● | ● | ● | | ● | ● |

TECHNOLOGY PROGRAM ELEMENTS — AVIONICS, SOFTWARE, AUTOMATION

| Vehicle | Guidance, navigation and control | Flight system management | System integration and verification | Communications | Vehicle system health monitoring | Data system architecture | Software | [illegible] | Sensors |
|---|---|---|---|---|---|---|---|---|---|
| SHUTTLE OPS WITH IMPROVEMENTS | ● | ● | ● | | | | ● | | |
| ADVANCED CARGO VEHICLE | ● | ● | ● | | | | ● | | |
| IMPROVED EXPENDABLE ELV | | ● | ● | | | | ● | | |
| OMV | ● | ● | ● | | | | ● | | ● |
| REUSABLE OTV | ● | ● | ● | | | | ● | | |
| HEAVY LIFT CARGO VEHICLE | ● | ● | ● | ● | | | ● | ● | |
| MANNED REUSABLE VEHICLE | ● | ● | ● | ● | ● | ● | ● | ● | |
| HIGHLY AUTONOMOUS OMV | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| SPACE BASED OTV | ● | ● | ● | ● | | ● | ● | ● | |

TECHNOLOGY PROGRAM ELEMENTS — GROUND/FLIGHT OPERATIONS

| Vehicle | Launch systems | Robotics | Payload transport containers | Propellant handling | Recovery | Environmental protection | Advanced mission operations | On-orbit servicing operations | Operations standardization |
|---|---|---|---|---|---|---|---|---|---|
| SHUTTLE OPS WITH IMPROVEMENTS | ● | ● | ● | ● | ● | ● | ● | | ● |
| ADVANCED CARGO VEHICLE | ● | ● | ● | ● | ● | ● | ● | | ● |
| IMPROVED EXPENDABLE ELV | ● | | | | | | | | |
| OMV | ● | | | | ● | ● | | ● | |
| REUSABLE OTV | ● | ● | | ● | ● | ● | | ● | |
| HEAVY LIFT CARGO VEHICLE | ● | ● | ● | ● | ● | ● | ● | | ● |
| MANNED REUSABLE VEHICLE | ● | ● | ● | ● | ● | ● | ● | | ● |
| HIGHLY AUTONOMOUS OMV | ● | ● | | | ● | ● | | ● | |
| SPACE BASED OTV | ● | ● | | ● | ● | ● | | ● | |

TECHNOLOGY PROGRAM ELEMENTS — PROPULSION/POWER

| Vehicle | Propulsion test facilities | Liquid booster propulsion | [illegible] booster propulsion | Chemical OTV propulsion | Electrical OTV propulsion | Advanced propulsion | Advanced auxiliary propulsion | On-board power systems | [illegible] power systems | [illegible] |
|---|---|---|---|---|---|---|---|---|---|---|
| SHUTTLE OPS WITH IMPROVEMENTS | | ● | ● | | | | | ● | | ● |
| ADVANCED CARGO VEHICLE | ● | ● | ● | | | | | ● | | ● |
| IMPROVED EXPENDABLE ELV | | | ● | | | | | ● | | |
| OMV | | | | ● | | | | ● | | |
| REUSABLE OTV | ● | | | ● | | | | ● | | |
| HEAVY LIFT CARGO VEHICLE | ● | ● | ● | | | ● | | ● | | ● |
| MANNED REUSABLE VEHICLE | ● | ● | | | | ● | ● | ● | | ● |
| HIGHLY AUTONOMOUS OMV | | | | ● | | | | ● | | |
| SPACE BASED OTV | ● | | | ● | ● | ● | | ● | ● | ● |

TECHNOLOGY PROGRAM ELEMENTS — STRUCTURES/MATERIALS

| Vehicle | Structural test facilities | Cryogenic tankage | Hot structures | Reusable thermal protection | Control surfaces | [illegible] | Inflatable structures | [illegible] |
|---|---|---|---|---|---|---|---|---|
| SHUTTLE OPS WITH IMPROVEMENTS | | | | | | ● | ● | ● |
| ADVANCED CARGO VEHICLE | ● | ● | | | | ● | ● | ● |
| IMPROVED EXPENDABLE ELV | | | | | | | | ● |
| OMV | | | | | | | | ● |
| REUSABLE OTV | | ● | | | | ● | ● | ● |
| HEAVY LIFT CARGO VEHICLE | ● | ● | | | | ● | | ● |
| MANNED REUSABLE VEHICLE | ● | ● | ● | ● | ● | ● | | ● |
| HIGHLY AUTONOMOUS OMV | | | | | | | | ● |
| SPACE BASED OTV | ● | ● | | | | ● | ● | ● |

Table 4. Liquid Booster Propulsion Technology (Example)

CRITICAL DISCIPLINE TECHNOLOGIES WILL BE DEVELOPED FOR ADVANCED LOX/H2, LOX/HC AND LOX/HC/H2 LIQUID EARTH-TO-ORBIT (ETO) PROPULSION CONCEPTS. DESIGN METHODOLOGIES WILL BE ESTABLISHED AND EXPERIMENTALLY VALIDATED AT THE SUBCOMPONENT AND COMPONENT LEVELS. CRITICAL DISCIPLINES INCLUDE COMBUSTION STABILITY, PERFORMANCE, REUSABILITY, DURABILITY, COOLING, MATERIAL COMPATIBILITY, FUNCTIONALITY AND PRODUCIBILITY. SYSTEM LEVEL INTEGRATED TECHNOLOGIES WILL BE DEMONSTRATED THROUGH BREADBOARD TESTS CONCENTRATING ON TANK/FEED SYSTEM/ENGINE PERFORMANCE, LIFE, HEALTH, SUBCOMPONENT AND COMPONENT INTEGRATION EFFECTS, AND REFURBISHMENT REQUIREMENTS. GOALS INCLUDE A FACTOR OF TWO REDUCTION IN VEHICLE DRY WEIGHT RELATIVE TO CURRENT CRYOGENIC PROPULSION TECHNOLOGY.

ELEMENTS

ENGINE CONCEPTS (high thrust)
- LOX/H2
- LOX/HC
- LOX/HC/H2

TANK CONCEPTS

FEED SYSTEMS

ENGINE CONTROLS

ENGINE HEALTH MONITOR

TEST FACILITIES

RECOVERY SYSTEMS

FUNDING ($M)

| FISCAL YEAR | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CURRENT* | 26 | 34 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 340 |
| AUGMENTED | 28 | 46 | 50 | 95 | 95 | 47 | 35 | 35 | 35 | 35 | 511 |

MILESTONES

△1 △2 △3 △4 △5

1. CONCEPT SELECTED
2. SUBCOMPONENT TECHNOLOGY AVAILABLE
3. COMPONENT TECHNOLOGY AVAILABLE
4. BREADBOARD TESTS COMPLETED
5. SYSTEM TECHNOLOGY AVAILABLE

SYSTEM PAYOFFS

- REDUCES VEHICLE DRY/GROSS WEIGHTS
- REDUCES LAUNCH OPERATIONS
- EXTENDS LIFE
- ENABLES SINGLE STAGE TO ORBIT
- ENABLES REUSABLE LIQUID BOOSTER

*Primarily currently planned Shuttle SSME improvements.

scenarios using prototype systems when practical. Indeed, few systems have successfully embraced radical new technology unless preceded by comprehensive demonstration programs.

In general, each demonstration incorporates a number of advanced technologies, both hardware and software, and may also utilize new operational concepts. Aeroassisted orbital transfer systems and precision recovery systems are specific examples of new technology applications wherein the lowered risks offered by demonstration programs could be important. Demonstration programs supportive of near- and far-term systems are presented and related to generic vehicles to which they contribute in Table 5.

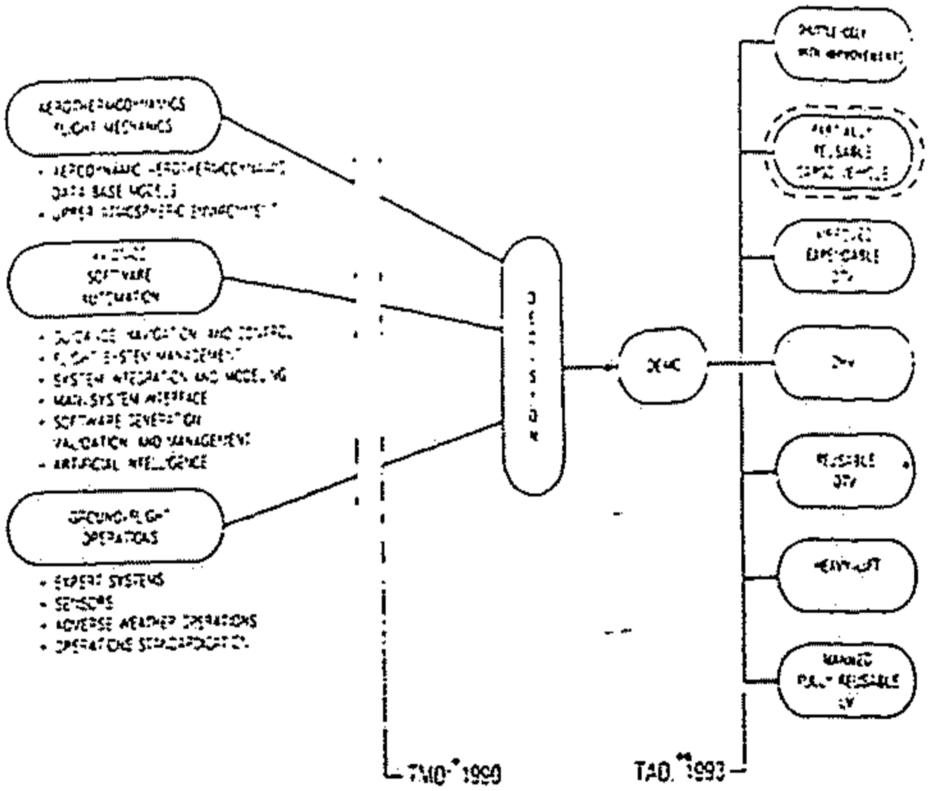
The proposed technology plan builds on relevant ongoing funded programs in government and industry. The program elements have been carefully structured to complement these activities and to avoid duplication. The following are representative of current programs which are critical to future U.S. space transportation activities. The National Aero-Space Plane (NASP) Program deserves special emphasis in that, from its inception, it has embodied both an aggressive, focused technology maturation effort and a firm national decision point for moving into a technology demonstration flight program. The NASP provides for the technical base necessary to develop an advanced airbreathing propulsion system, for revolutionary materials development, for major advances in lightweight hot structures, and for hypersonic vehicle design. Other programs include the $LO_2/LH_2$ Rocket Test Bed Program, which will increase engine performance, life, and reusability; the Storable OTV Engine Demonstration Program, which will yield an advanced technology pump-fed engine; and the Space-Based Cryogenic Engine Program, which will validate advanced cryogenic expander-cycle OTS engine concepts. The On-Orbit Fluid Management Demonstration builds on a current NASA experiment scheduled for flight in 1989. The Avionics, Software, and Automation Program proposed in the present plan builds on Space Station activity in automation and robotics and is structured to complement related activities in the Defense Advanced Research Projects Agency (DARPA) and the aerospace industry.

o Program Schedules and Funding

The technology program elements and the demonstration programs are scheduled to support the architectures and related generic vehicles. The program elements and demonstration programs which support each generic vehicle class are identified in Tables 3 and 5. The way in which selected demonstration programs focus a wide range of disciplinary activities to make key technologies available is illustrated for the case of the Partially Reusable Cargo Vehicle in Figures 3 and 4. The architectures studies show large potential cost savings resulting from automated launch/flight operations (which

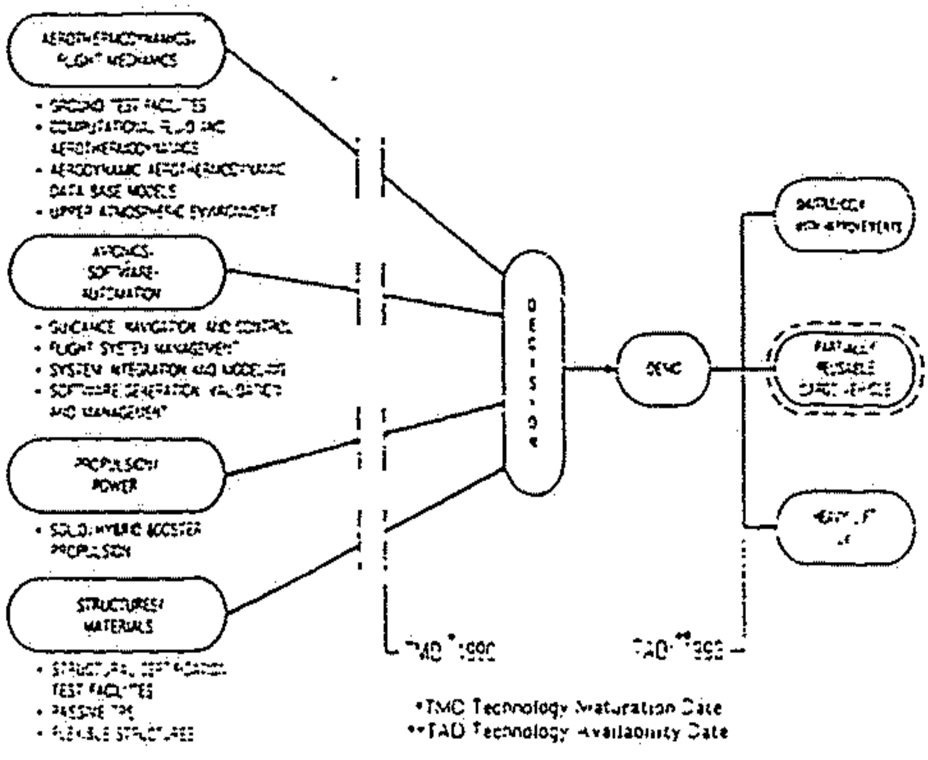
Table 5. Technology Demonstration Programs vs. Generic Vehicles

| | | | Vehicle Types | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pre 2000 | | | | | Post 2000 | | | |
| | | | Shuttle/CLTV with Improvements | Unmanned Cargo Vehicle | Improved Expendable OTS | OMV | Reusable OTS | Heavy Lift Cargo Vehicle | Manned Reusable Vehicle | Highly Autonomous OMV | Space Based OTS |
| Technology Demonstration Programs | Supporting Near Term Systems | Automated Launch/Flight Operations | ● | ● | ● | ● | ● | ● | ● | | |
| | | On-Orbit Fluid Management | | | | ● | ● | | | ● | ● |
| | | Proximity Operations | | | | ● | ● | | | ● | ● |
| | | LOX/$H_2$ and LOX/HC Test Beds | ● | ● | | | | ● | ● | | |
| | | Clean/Low Cost Solid Rocket | ● | ● | ● | | | | | | |
| | | Aeroassist OTS Flight Experiment | | | | | ● | | | | ● |
| | | Storable OTS Engine | | | | ● | ● | | | ● | ● |
| | | Precision Recovery Systems | ● | ● | | | | ● | | | |
| | | Computer Integrated Manufacturing | ● | ● | ● | | | | | | |
| | Supporting Far Term Systems | Autonomous Space Operations | | | | | | ● | ● | ● | ● |
| | | High Orbit Servicing | | | | | | | | ● | ● |
| | | High Thrust Reusable Liquid Rocket | | | | | | ● | ● | | |
| | | National Aero Space Plane | | | | | | | ● | | |
| | | Maneuverable Entry Research Vehicle | | | | | | | ● | | |
| | | Full-Scale Thermostructure/Cryotankage | | | | | | ● | ● | | ● |
| | | Space Based Cryogenic OTS Engine | | | | | | | | | ● |



*TMD Technology Maturation Date
**TAD Technology Availability Date

Figure 3. Automated Launch/Flight Operations Demonstration



*TMD Technology Maturation Date
**TAD Technology Availability Date

Figure 4. Precision Recovery Systems Demonstration

drastically reduce present high manpower loadings) and from precision recovery (and hence reuse) of high-cost booster elements such as rocket engines and avionics subsystems. As shown, these two demonstration programs achieve technology maturity and technology availability dates which support deployment of a new Partially Reusable Cargo Vehicle in the mid- to late-1990s. The synergism of the proposed technology program wherein individual program elements and demonstration programs support several vehicle classes is also illustrated in Figures 3 and 4. This synergism makes the present technology plan essentially vehicle and architecture transparent.

Funds expected from projected NASA/DoD budgets, as well as the total amounts required to meet milestones with moderate schedule risk, have been identified for each of the technology program elements. Total recommended program costs (exclusive of new demonstration projects) for the current 5-year period (FY 1987-1991) and 10-year period (FY 1987-1996) are estimated to be $3-4 billion and $5-6 billion. These total costs include near-term investments in upgraded and new ground test facilities for the acquisition of vital data and preflight certification of complex new systems and are complementary to those of the NASP Program. This technology plan has been structured to avoid overlap with the NASP Program. Total cost of the plan is a small fraction of the cost of any new transportation architecture.

## 6. FINDINGS

The key findings from this study are:

- The existing Shuttle/CELV/Other ELVs launch vehicle architecture has relatively high operating costs when compared to that achievable in the 1995 to 2010 time period. Although its continued use would require no significant development investments, anticipated traffic growth would necessitate high Shuttle/CELV flight rates and sizable investments in additional orbiters, expendables, ground processing and launch facilities, and operations support.
- Many technologies critical to the future of space transportation are poised for major advances that could greatly benefit both existing and new systems in the post-1995 time period.

- o Current funding levels severely inhibit the timely development of a majority of necessary key technologies.
- o Facilities in the areas of propulsion, structures, and aerothermodynamics are demonstrably inadequate to cope with development testing requirements inherent in the realization of complex new technologies and systems.
- o Future U.S. launch systems design must be driven by operations and support as well as assured access considerations, which may include launch sites within the interior of the United States, in order to achieve operational flexibility and cost effectiveness. A substantial reduction in recurring operations cost is achievable if launch vehicles are designed for operational efficiency rather than maximum performance.
- o Mission models should not be evaluated based on total tonnage to orbit alone. Frequency of flight and payload sizes should play a role in the architecture. Modularity of vehicles and payloads may provide increased operational flexibility.
- o Preferred architectures employ two new launch systems, an unmanned cargo vehicle and a new manned vehicle (with supplementary use of ELVs for specific missions); a new reusable OTS; and new launch and flight operations approaches. This architectural approach is cost effective across a wide range of mission scenarios and would improve assured access capabilities.
- o Integration of payloads with the launch system is a significant operational cost. New processing and integration methods approaching those applied to cargo aircraft and other truly "operational" transportation systems must be developed.
- o Numerous system and technology options must be explored in parallel to enable selection of a future U.S. space transportation architecture.
- o The generic technology investment plan required to achieve low operations cost, robustness, flexibility, and world leadership in space transportation has been defined. The recommended plan provides a road map with decision dates for final architecture selection.
- o Implementation of the recommendations of this report will assure that the U.S. has a solid beginning toward revitalizing its national launch systems technology and industrial base and retaining uncontested leadership in space.

# 7. RECOMMENDATIONS

The Joint Steering Group recommends the following:

- o If new manned and unmanned launch systems and lower costs for space launch operations are to be attained, the U.S. must commit to implementing the technology plan of this report. This plan, which is complementary to other firmly planned technology activities (e.g., the National Aero-Space Plane Program, ongoing DoD/NASA programs, and industry programs), is focused to provide a base for new systems which can achieve the objective of substantially reduced operations costs. The plan supports the development of both evolutionary and revolutionary technology alternatives necessary to assure continued U.S. world leadership in space transportation.
- o Maintain the DoD/NASA Joint Steering Group (JSG) to guide the national efforts toward a second-generation space transportation system. Establish a more permanent organizational structure, which would replace the current Ad Hoc Joint Task Team, to further refine the future space transportation architecture, coordinate technology activities, and coordinate plans for new systems as the need arises and technology becomes available. The JSC must also ensure that close coordination/liaison is maintained with the National Aero-Space Plane Program Office, the Strategic Defense Initiative Organization, and other appropriate DoD and civil offices. Additionally, continued ties must be established with all space transportation users to ensure that transportation-related issues such as spacecraft modularity, standardization, containerization, and servicing are addressed from an overall space program perspective, including identification of needed technologies. Provide for mutual DoD/NASA approval of the structure, staffing, and location for the organization.
- o Continue the joint NASA/DoD Space Transportation Architecture Studies to include:
  - o Conduct trade studies and sensitivity analyses to refine and confirm the cost beneficial investments which will provide the most efficient operations and vehicle systems for the future.

- o Reassess the transition to the next generation space transportation systems while considering all elements of the architecture and the current Space Shuttle and Titan recovery plans.
- o Develop planning to accommodate the unique military operational and functional needs of Unified Space Command and SDI as these needs evolve.
- o Preserve the option for a near-term space transportation architecture to accommodate potential deployment options for Strategic Defense Initiative systems and meet other increasing civil and DoD launch demands on a cost-effective basis.

o Direct that the study results be reviewed by the space transportation user community for applicability to spacecraft production/operations.